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# INVESTIGATION OF 15 KV AIR-MAGNETIC BREAKER FAILURES

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Recent failures of feeder breakers at Lake TS and Birmingham TS during periods of lightning activity were investigated. No evidence of a breaker malfunction was found. The switching duty for conventional faults has been assessed and is expected to have been within breaker ratings. It is postulated on the basis of circumstantial evidence that the breakers failed due to evolving faults associated with lightning activity. A recent failure of an Ottawa Hydro owned air-magnetic breaker was also reviewed because of its possible relevance to the Ontario Hydro failures. This breaker failed on a closing operation, but it is possible that it had been damaged during earlier switching operations. As a consequence of this investigation, concerns have been identified regarding possible deficiencies in existing circuit breaker standards. However these are not considered a factor in these failures.

## 1. INTRODUCTION

An Air-Magnetic (AM) feeder breaker failed recently at each of Lake TS and Birmingham TS during periods of lightning activity. Inspection of the failed breakers revealed evidence of similar arcing damage below the arc chutes involving the bus side connections and the nearby grounded frame. We were asked by the Transmission Operations Division to investigate these failures in order to identify possible causes and, if appropriate, to recommend remedial measures. In the course of these investigations, we also reviewed a recent failure of an Ottawa Hydro owned AM breaker at Lincoln-Heights TS because of its possible relevance to the Ontario Hydro failures.

This report presents the results of our investigation. We have based our assessment on the available evidence, on the expected switching duty, and on the expected breaker capabilities as provided for by the relevant circuit breaker standards/1-5/. A review of the standards has also raised some concerns which are identified along with recommendations for addressing these concerns.

On the basis of the available evidence it appears that the breakers at Birmingham TS and Lake TS failed while interrupting evolving faults on the associated feeders. This represents a duty not covered under the relevant standards, and a duty under which AM breakers may be prone to failure. The Ottawa Hydro failure appears to have occurred on a closing operation, presumably because it was in a damaged state from earlier switching operations.

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## 2. DESCRIPTION OF INCIDENTS

### 2.1 Failures at Birmingham TS and Lake TS

On July 30, 1988, a 750-MVA Federal Pioneer Type DST-2 AM breaker on feeder M7 failed at Birmingham TS during a period of lightning activity. A similar 500-MVA Federal-Pioneer Type DST-2 AM breaker failed at Lake TS on August 11, 1988 during lightning activity. Both failures occurred under similar circumstances and resulted in similar damage internally to the breaker assembly. Extensive arcing damage was found below the arc chutes, including flashovers from connections between the arc runners and the blowout coils to the grounded parts of the breaker carriage. The blowout coil circuit and the arc chutes appeared intact and in good working condition.

In each case, the tripping operation on the breaker was accompanied by operation of three-phase instantaneous overcurrent feeder protection, presumably because of a fault initiated by a lightning strike. The breaker evidently failed while attempting to clear this fault, and was eventually isolated by bus differential protection which includes the breaker within its coverage zone.

It is our understanding that automatic reclosure is blocked on all 13.8 kV feeders in the Hamilton area. Therefore the breaker failed on the initial fault-clearing attempt. The distribution feeders at these stations are relatively short in length (a little more than a kilometre) and may include up to one-half kilometre of cable. Operating voltage in the Hamilton area is about 14.2 kV.

### 2.2 Failure at Lincoln-Heights TS

On July 26, 1988, a 500-MVA ITE Type HK breaker failed when it was closed manually. Bus differential protection operated to trip the breaker along with the associated supply to the bus. Inspection revealed extensive damage to the arc chutes. Flashovers had evidently occurred between the terminal points of the magnetic blowout coils and the rear of the metalclad, sufficient to melt the coil connections/6-9/.

There is no evidence that a fault existed on the feeder at this time since feeder protection did not operate, and also because the feeder was picked up later without incident. Only the bus differential protection operated on blue and white phases, which isolated the faulted breaker.

About three hours prior to the failure, the breaker had successfully cleared a feeder fault during lightning, and carried out two unsuccessful reclosure operations. The automatic reclosures were carried out under the existing OCO-15-CO scheme, following which the breaker was locked in the open position. Protective relaying was found to have operated on timed overcurrent protection on all three phases. A phase conductor was found severed and was repaired. No breaker inspection was carried out before attempting the subsequent closing operation which resulted in the failure. The normal operating voltage at the station is about 13.2 kV.

## 3. REVIEW OF FAULT INTERRUPTING DUTY AND BREAKER CAPABILITIES

The supply to the 13.8 kV bus at all three stations is through wye-connected reactor-grounded secondaries such that the fault interrupting duty approaches that expected on an ungrounded system/10/. The following discussion reviews the expected switching duties relative to the interrupting capabilities provided for by the relevant standards/1-5/.

## 3.1 Fault Current Duty

According to the System Planning Division, the 3ϕ symmetrical fault levels at Birmingham TS and Lake TS are 597 MVA and 442 MVA respectively at 14.2 kV. The fault level at Lincoln-Heights TS is about 303 MVA at 13.2 kV. These are within the respective breaker ratings.

## 3.2 Transient Recovery Voltage (TRV) Duty

Existing standards recognize that the maximum theoretical TRV across the first pole to open is 3 pu when clearing a 3ϕ ungrounded fault (or a 3ϕ grounded fault on an ungrounded system). The TRV values encountered in practice are lower because of damping due to losses in step down transformer(s) and station load, and because of system regulation. On this basis, the standards require that breakers rated less than 72.5 kV interrupt successfully at rated voltage in a circuit with an inherent TRV crest value equal to 1.88 times the rated maximum voltage. The term "inherent TRV" describes the natural circuit behaviour, without including the modifying effects introduced by the interrupting device (eg. due to opening resistors or arc dynamics). The specified TRV capability corresponds to 2.3 pu of the peak L-G voltage at rated voltage/3,4,11/.

Test reports provided to us for Type DST-2 breakers confirm that this breaker has been tested successfully for 3ϕ fault interruption duty on an ungrounded system/12,13/. The peak TRV impressed upon interrupting rated current at rated voltage was about 1.8 pu (based on 12.2 kV peak L-G at 15 kV test voltage) in tests on a 750 MVA breaker, and 2.4 pu in tests on a 500 MVA breaker.

In our opinion, the peak circuit TRV for these feeders is unlikely to exceed 2.3 pu of the peak L-G operating voltage. The feeders are relatively short in length (about 1 km), therefore faults on these feeders are electrically close to the station bus. For close-in faults, a large fraction of the recovery transient occurs on the bus side of the breaker terminals. The transient is expected to follow a classic 1-cosine (one minus cosine) waveshape, and to overswing by no more than 20% due to damping provided by the station load/14/. On this basis, the TRV duty is expected to have been within the proven capabilities of the feeder breakers.

## 3.3 Rate of Rise of Recovery Voltage (RRRV) Duty

Requirements for RRRV capability are not specified in the relevant standards for indoor oilless breakers rated below 72.5 kV. In its absence, we have based our assessment on test reports for Type DST-2 breakers. These show that the breaker is able to interrupt 3ϕ ungrounded faults at rated voltage for current levels ranging from 10% to 100% of the rating. The inherent circuit RRRV ranged from 0.03 to 0.61 kV/μs, corresponding to TRV frequencies of 1.2 kHz to 13.3 kHz. Our simplified calculations show that TRV frequencies for feeder breakers at Birmingham TS and Lake TS are likely to be about 2.5 to 3 kHz, and are therefore within the tested range. Our calculations assume that there are no major 13.8 kV capacitor banks in the vicinity, as we have been informed, either at our stations or at customers' premises. If significant shunt capacitive compensation were present, TRV frequencies could be lowered possibly to values below the tested range. This could be of concern in view of a failure mechanism identified by Greenwood et al in their investigations of General Electric AM breaker failures/15/. These investigations show that AM breakers may be vulnerable at low values of RRRV (TRV frequencies below about 1 kHz) such as those typically encountered in heavily cabled systems or in systems with significant shunt capacitive compensation.

### 3.4 Automatic Reclosing Duty

As noted previously, automatic reclosure was blocked at Lake TS and Birmingham TS at the time of these failures. At Lincoln Heights TS on the other hand, it is known that the breaker carried out two unsuccessful reclosures before failing on the subsequent manual closing attempt. Circuit breaker standards were therefore reviewed to assess the impact of reclosure schemes.

Breakers in this voltage class having continuous current ratings less than 1200 A are required to meet their standard of interrupting performance when carrying out a "Standard Duty Cycle" consisting of " ...two unit operations with 15 s interval between operations (CO - 15 s - CO)"/1/. For reclosing schemes requiring more operations or shorter intervals of time between operations, the Standard provides a means of derating breaker interrupting capabilities to ensure successful application.

The reclosing scheme implemented at Lincoln-Heights TS (OCO-15-CO) exceeds the standard duty cycle by one opening operation. For this duty, the maximum symmetrical current interrupting capability is required to be derated to about 96 to 97% of the nameplate rating, but this is still adequate for the short circuit level at Lincoln Heights TS. It is therefore concluded that a breaker in good working condition should have been able to perform the required reclosing cycle at this station without incurring damage.

## 4. ASSESSMENT

### 4.1 Lincoln-Heights Failure

Available evidence suggests that the failure did not occur during an opening operation. The breaker failed shortly after it was closed manually. It apparently did not open until initiated by bus differential protection following internal flashovers. Feeder protection did not operate, therefore, there was no fault on the feeder and no reason for the breaker to have been opening when it failed.

In order for the breaker to have failed on closing, it seems that either the closing mechanism had to malfunction, or the breaker had to be in a damaged state already. Since there is no evidence of the former, we favour the latter. More specifically, it is possible that the dielectric strength to ground for the load side of the interrupter was impaired during the preceding switching operations with the faulted feeder. The precise cause for such damage is difficult to identify with certainty, but it is possible that the breaker experienced difficulty in an earlier opening operation, perhaps due to one of the mechanisms postulated for the Ontario Hydro failures in the following discussion.

### 4.2 Ontario Hydro Failures

There is no evidence of a breaker malfunction. The FPE type DST-2 breaker appears suited to this application and has been tested in accordance with the standard requirements. It should therefore be capable of interrupting a conventional 3$\phi$ ungrounded fault in this application. The term "conventional", as used here, describes a permanent fault on all three phases prior to the breaker being tripped and its contacts parting. This is the type of fault considered in establishing the relevant standards, and it is the type of fault duty for which a circuit breaker is tested. However, the fact that the breaker still failed raises the possibility that the switching duty in these instances may have exceeded that recognized by standards, either because the imposed duty is not sufficiently understood or because the nature of the fault is different. At the moment we have no evidence for the former, but can cite an example for the latter.

A type of fault considered particularly difficult for AM breakers is one in which the fault current changes abruptly while the breaker contacts are parting and arcing has commenced across its contacts. This is termed an evolving fault. It is a duty under which AM breakers can fail according to our discussions with Dr. Greenwood, the co-author of the publication referenced earlier/15/. The possibility of this type of fault having been involved in the two failures is consistent with the circumstances under which the breakers failed. In both incidents, lightning had struck the associated feeder and the fault had (eventually) involved all three phases. If the strike were a direct hit to a phase conductor, it is expected that all phases would become faulted within microseconds due to flashovers across line insulators, and the fault duty would be no different than that recognized by the standards. However, in case of an induced flashover (due to lightning strike in the vicinity of the feeder), all three phases may not become faulted immediately. Initially, the fault could involve perhaps one or two phases. However, arcing due to this fault could eventually cause all phases to be faulted. This could pose a problem if the remaining phase(s) become faulted a sufficient duration after breaker contacts have parted and commenced arcing.

Another possibility is a subsequent lightning stroke to the feeder. Literature/16,17/ suggests that 55% of lightning flashes include more than 1 stroke. The mean number of strokes per flash is 3. The most frequent interstroke interval is 30 - 50 ms, and the median duration for a 3-stroke lightning flash is about 80 ms. In comparison, fault interrupting time for breakers in this voltage class includes about 16 ms relaying time plus up to 80 ms rated interrupting time. It is evident from these figures that a possibility exists for a subsequent lightning stroke to arise during the critical period when the arc across the breaker contacts has just extinguished. In this event, a breakdown could occur across the contacts such that the resultant arc fails to transfer to the arc runners. The magnetic blowout coil circuit is therefore bypassed, allowing the arc to continue to burn outside the arc chutes and eventually to cause a dielectric failure to ground.

An evolving fault mechanism involving lightning therefore appears to be a plausible explanation for the failures at Birmingham TS and Lake TS. It is consistent with the available evidence and the circumstances surrounding the failures. It does not presume a breaker malfunction, for which there is no evidence. Finally, it does not presume that the breaker failed under a fault duty for which it has been tested and proven. Unfortunately, there is no simple means of confirming that this mechanism exists in practice. There are also no simple solutions for guarding against its consequences. Hence occasional breaker failures due to this mechanism may have to be accepted over the foreseeable future. If the failures are considered unacceptable, consideration could be given to substituting SF6 or vacuum breakers which may be less vulnerable to this type of fault duty.

## 5. RECONCILIATION OF STANDARDS' REQUIREMENTS WITH IMPOSED TRV DUTY

Except for the evolving fault duty, the standards and their supporting references appear to give adequate consideration to typical variations in system configurations and fault types. However, we are not certain that sufficient allowance has been made for the peak circuit TRV possible in some applications. A peak value of 2.3 pu has been adopted in standards, but this appears to be marginal or perhaps inadequate according to our simplified analysis. For example:

(a) For a 3$\phi$ fault on an ungrounded system, a peak TRV of 3 pu is theoretically possible across the first pole/10/. In practice this is limited to lower value due to system damping. Taking as an example a fault several kilometres from a station (on a long feeder) such that feeder impedance to the fault approaches the bus-side source impedance, the bus voltage during the fault is 0.5 pu. When the first pole opens, assuming a transient overswing of 20% on the bus side (damped by station load) and 60% on the feeder side, the peak TRV reaches 2.2 pu. Higher overswings due to lower damping (during light load periods) or more distant faults could produce a higher TRV.

(b) For a 3$\phi$ bus fault on an ungrounded system, the TRV on transformer breakers approaches 3 pu across the first pole, neglecting damping. The recovery transient is dominated by the voltage transient at the transformer terminals which is expected to be lightly damped. Assuming a conservative 70% overswing for the transformer-side transient/18/ and a 20% overswing for the bus-side transient gives a peak TRV of 2.3 pu.

(c) For a phase-to-phase bus fault on an ungrounded system, if the first pole of the breaker to open interrupts fault current, a 3.4 pu peak TRV is possible neglecting damping. If it is assumed that damping limits the overswing to 50%, the peak TRV reaches 2.6 pu.

While these faults appear to have been recognized in establishing the standards/1-5,10,11/, there does not appear to be sufficient documentation justifying the adoption of a 2.3 pu peak TRV level. Supporting references suggest simply that system regulation and inherent damping limit the TRV level encountered in practice. However more recent references appear to question this decision, suggesting that damping may not always be so pronounced, allowing peak TRV to reach 3 pu/18-20/.

We are also concerned that no specification is provided in the standards for the RRRV for circuit breakers rated less than 72.5 kV. This is particularly crucial for transformer breakers which are typically subjected to large RRRV for faults on the bus side of the breaker/18-20/.

## 6. SUMMARY & CONCLUSIONS

(1) In the absence of any evidence of a breaker malfunction, or evidence that the conventional fault interrupting duty for feeder breakers at Lake TS and Birmingham TS exceeds breaker ratings, an evolving fault mechanism associated with lightning strike on the feeder has been identified as a possible cause for the breaker failures.

(2) The breaker failure at Lincoln Heights TS appears to have occurred on a closing operation, presumably because the breaker was already in a damaged state from earlier switching operations.

(3) Concerns have been identified regarding possible deficiencies in existing breaker standards. While these are not considered a factor in the current failures, they may be an issue for other existing and future applications of breakers rated less than 72.5 kV.

## 7. RECOMMENDATIONS

Concerns have been identified regarding the adequacy of existing circuit breaker standards. In addition, a mechanism to account for recent breaker failures has been suggested, but its existence is unproven. In view of these uncertainties, and because of the adverse consequences of continued breaker failures, we recommend that investigations associated with these failures continue on two fronts:

(1) A means of confirming the evolving fault mechanism associated with lightning should be considered. This could involve setting up automatic recording equipment at selected sites.

(2) Consideration should be given to conducting low-voltage tests at selected site(s) to quantify the TRV duties encountered in practice. This would also serve to confirm that the encountered switching duty is within rated breaker capabilities. The objectives of these studies would be as follows:

   (a) To quantify peak TRV and RRRV in typical Ontario Hydro applications. This would require detailed analysis possibly using computer simulations to study mechanisms. Low voltage tests would be conducted at selected site(s) to support analytical modelling and to measure the TRV and RRRV directly.

   (b) Review existing breaker applications in view of the results of field tests.

   (c) If warranted by results of the field tests, develop specifications for peak TRV and RRRV for internal use. It is our understanding that Ontario Hydro has only recently decided to include an RRRV specification of 2 kV/μs for terminal faults for 15 kV metalclad switchgear. No peak TRV requirement other than that required under the existing ANSI standards is specified.

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